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Remote Sensing and Imaging Physics

7 March 2012

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Report Documentation Page

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Sub-Areas in Portfolio

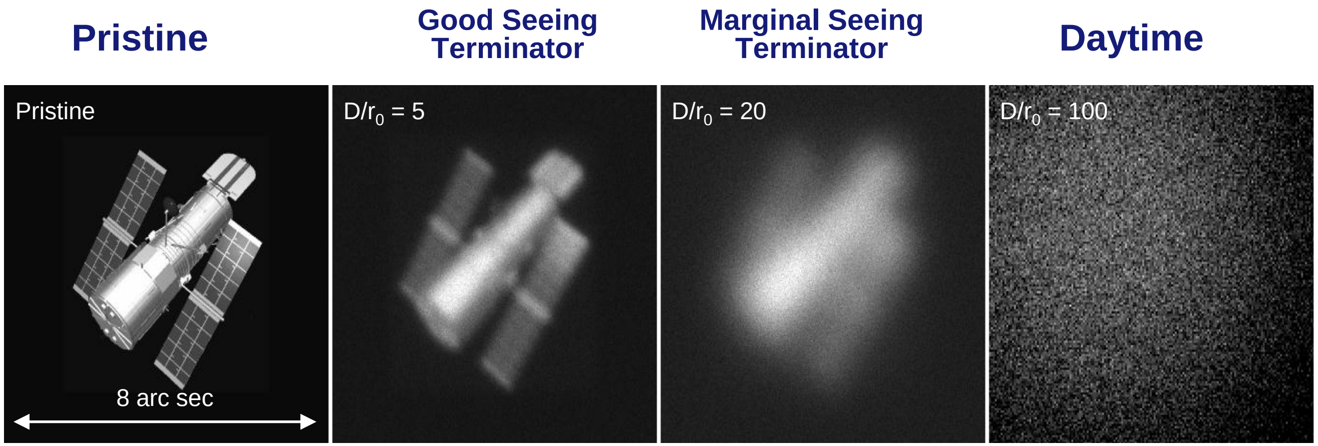
- **Observing and Identifying Space Objects**
  - Improved Imaging of Space Objects
  - Information without Imaging
  - Predicting the Location of Space Objects

- **Remote Sensing in Extreme Conditions**
  - Propagation Through Deep Optical Turbulence
  - Beam Control

Understand the physics that enables space situational awareness

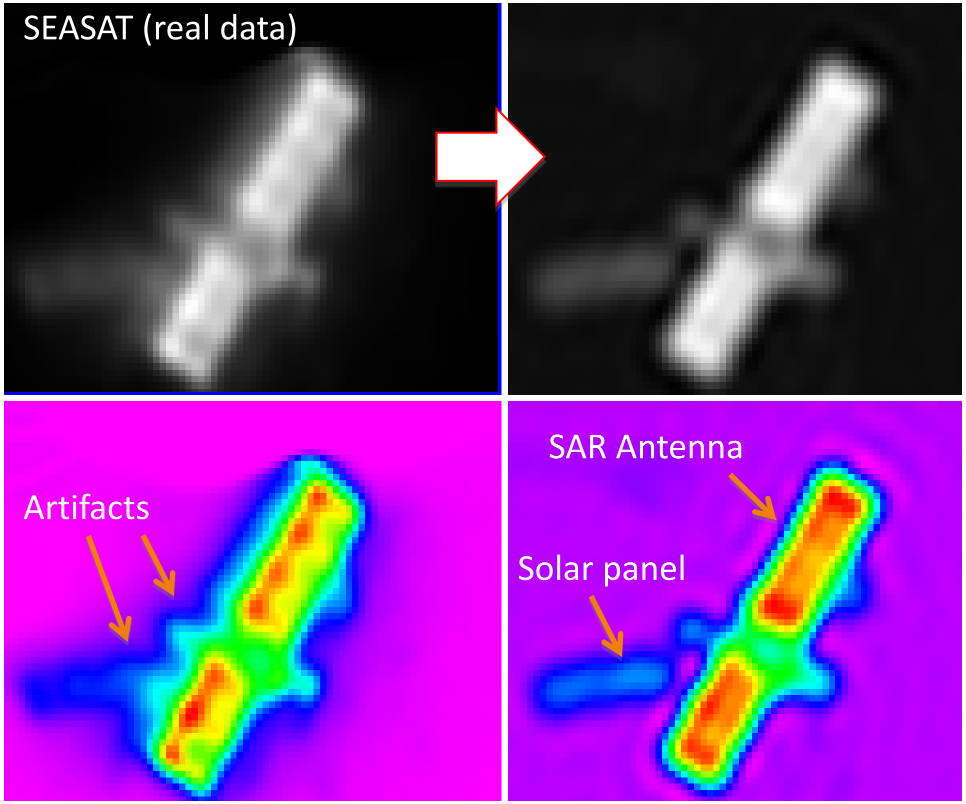
Understand the propagation of electromagnetic radiation and the formation of images

Improved Imaging of Space Objects

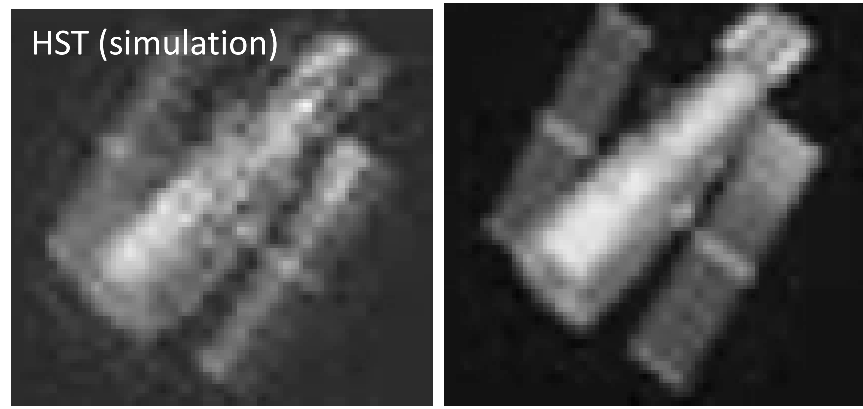


Simulations of the Hubble Space Telescope as it would appear from the 3.6 m AEOS telescope at a range of 700 km in 1 ms exposures at 0.9 μm wavelength under a range of seeing conditions.

Improved Extraction of Information from ground-based SSA imagery



Current capability   New capability



Current capability using data from 3.6m alone (D/r_0=27)

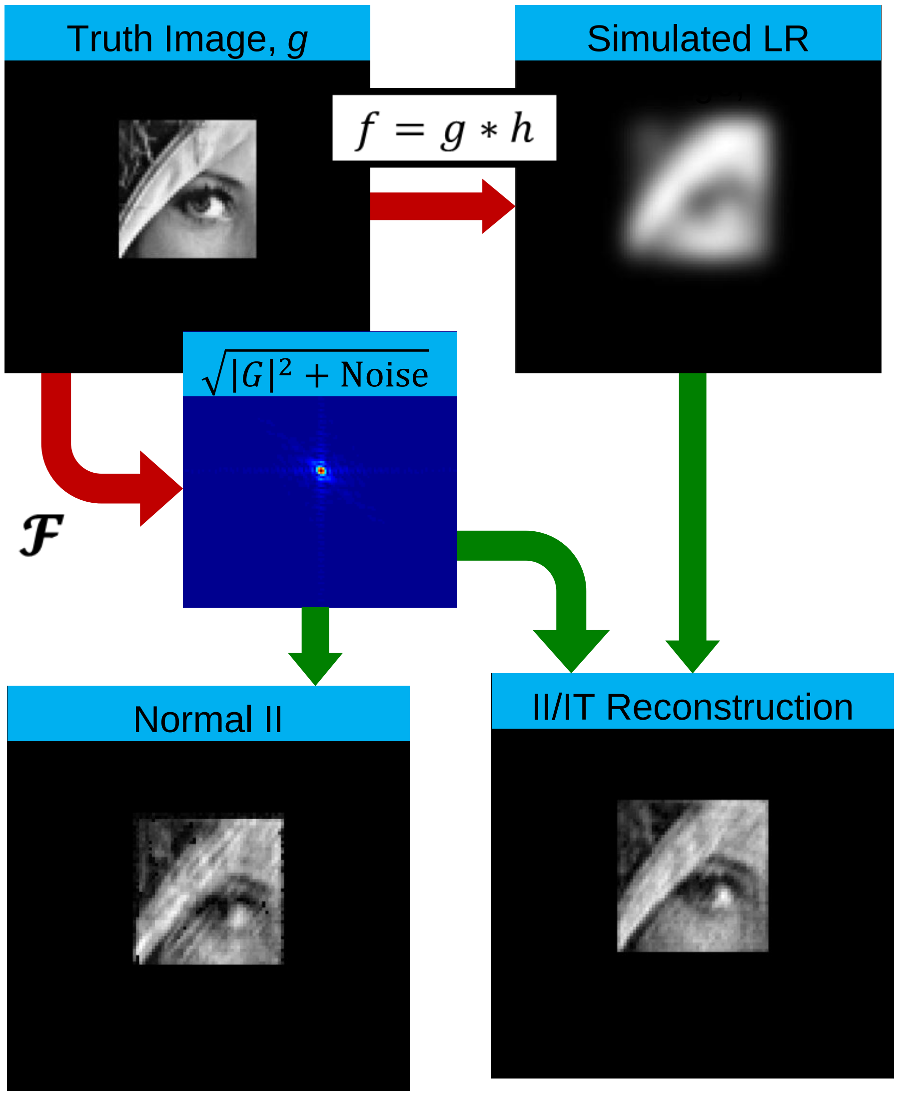
Proposed capability using data from both the 3.6m and 1.6m

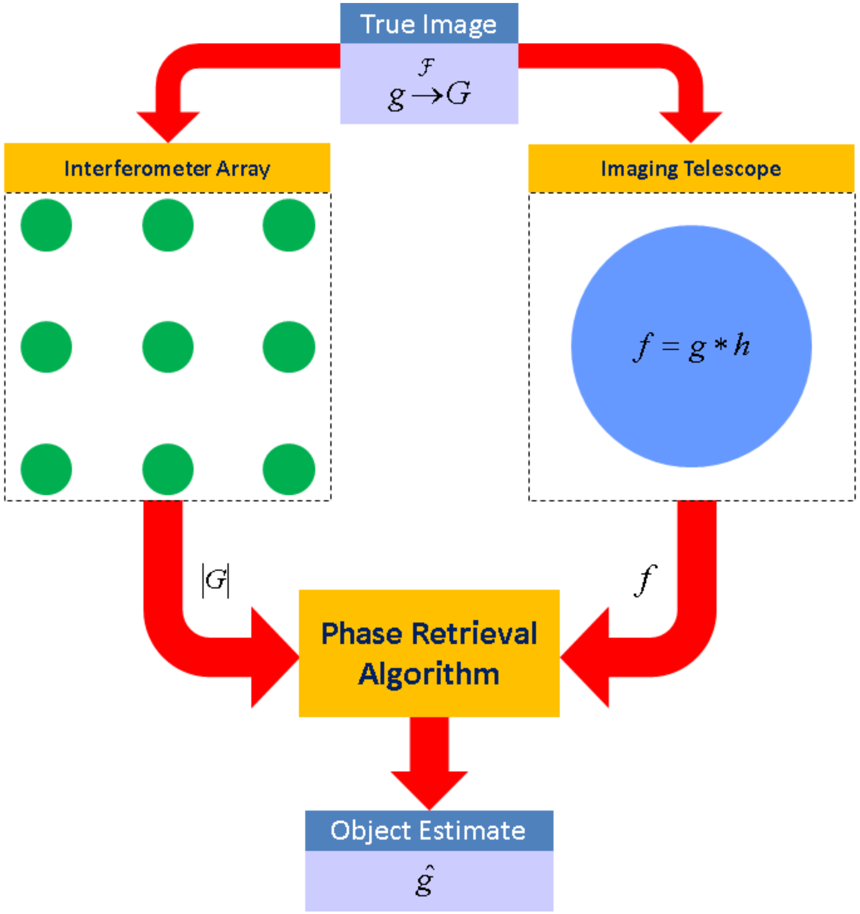
Leveraging AF telescopes in proximity

- Add Resolution diversity (multiple telescopes)
- Enforce intra- and inter-channel consistency
- Maintain high-resolution under strong turbulence

Potential to push SSA capabilities to severe seeing conditions ($D/r_0 > 30$)

Augmented Hybrid Input-Output Phase Retrieval

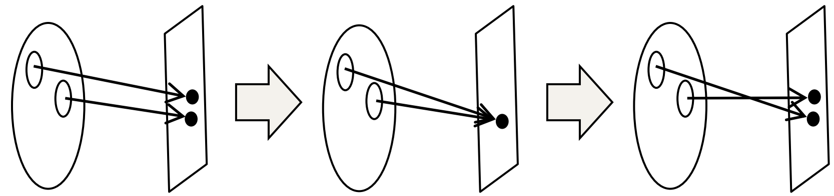




Local Maxima Structure of Wavefront Estimation

Each speckle associated with subset of pupil.

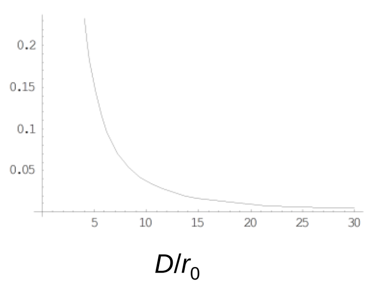
Each maximum corresponds to one mapping of subsets to speckles.



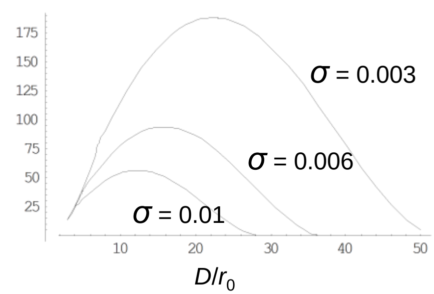
Provides physical description of the local maxima associated with speckle imaging estimation problems

Allows properties of local maxima to be derived from the Kolmogorov model of atmospheric turbulence:

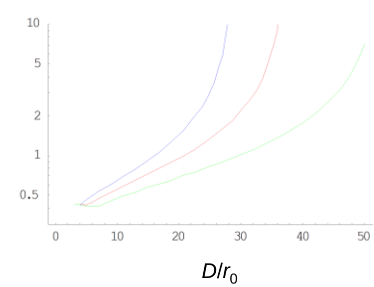
Expected distance between local maxima



Optimal number of modes



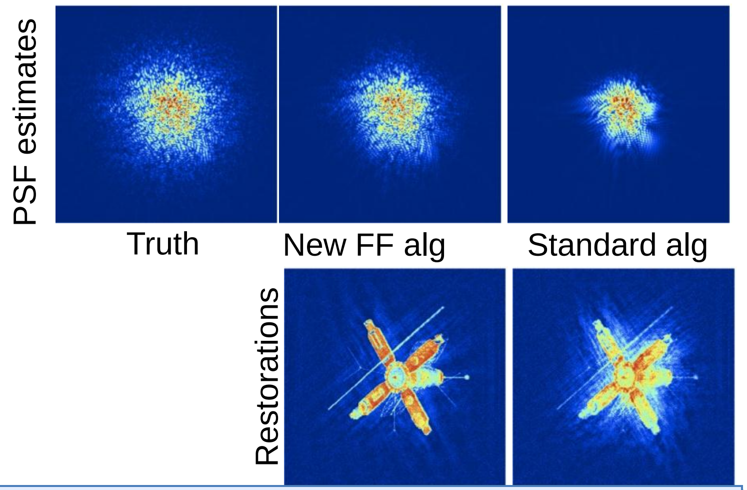
Wavefront estimation error



Chuck Matson, AFRL/RDS
Brandoch Calef, Boeing

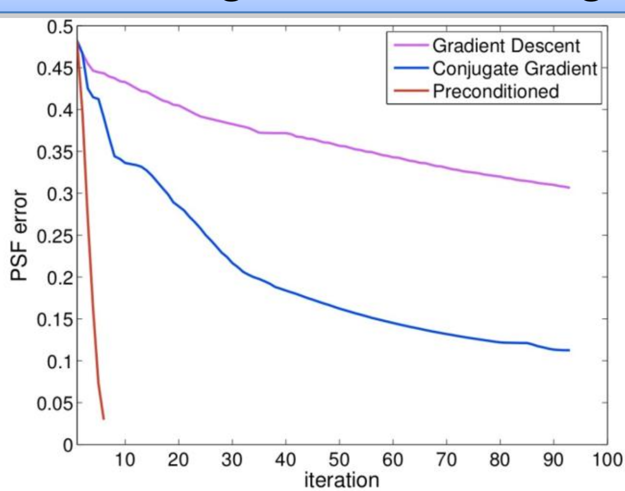
Algorithms for Multi-Frame Blind Deconvolution

Initial PSF Estimates using Wave Front Sensor



- ▪Properly defined constraints to define objective functions
- ▪Partial second derivative preconditioning
- ▪ *Implicit Filtering* (C.T. Kelley, SIAM, 2011) to avoid local minimum trap

Accelerating MFBD Convergence



- **Faster convergence with higher likelihood of achieving the global minimum.**
- **Improved quality of image restorations.**
- **Extended limits of SSA imaging capabilities.**

James Nagy, Emory University
Stuart Jefferies, University of Hawaii

Information without Imaging

Challenge:

-Limited information on each object
-Few sensors for a big space
-Cost of big telescopes, space-based sensors
-Lack of a priori knowledge
-Potentially massive data sets

Questions:

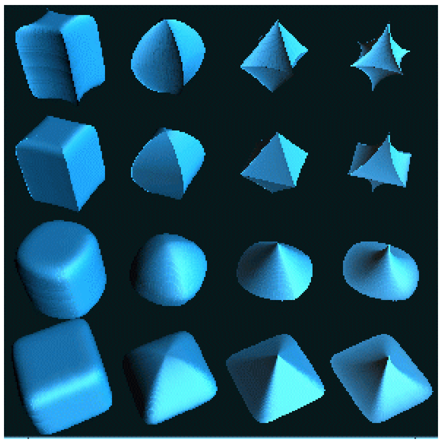
-How to extract information from an unresolved object
-How to search large/sparse data sets
-What information is needed, what is not needed
-Are there un-tapped sources of information

Path Forward:

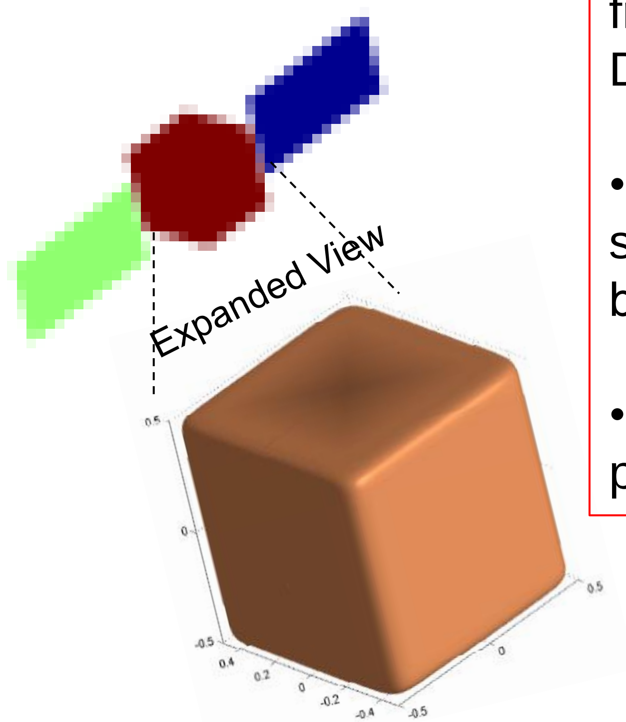
-Use of smaller, cheaper, more diverse sensors
-Sensor/Information fusion
-Information theory

Satellite Superquadrics Shape Estimation

$$\left[\left(\frac{x}{a_1}\right)^{2/\epsilon_2} \pm \left(\frac{y}{a_2}\right)^{2/\epsilon_2}\right]^{\epsilon_2/\epsilon_1} \pm \left(\frac{z}{a_3}\right)^{2/\epsilon_1} = 1, \quad \epsilon_1, \epsilon_2, \epsilon_3 \geq 0$$



Different super-ellipsoids from changing ε_1, ε_2, ε_3

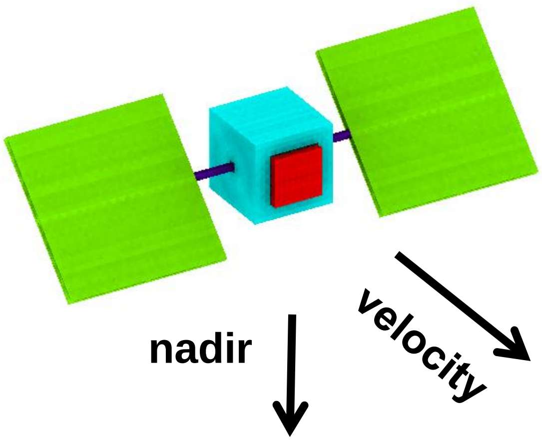


- Estimate rotational / translational motions from data via Fourier Descriptors
- Combine with body silhouettes, estimate body’s 3D convex hull
- Estimate superquadric parameters.

Superquadrics from computer vision simulate complicated surfaces

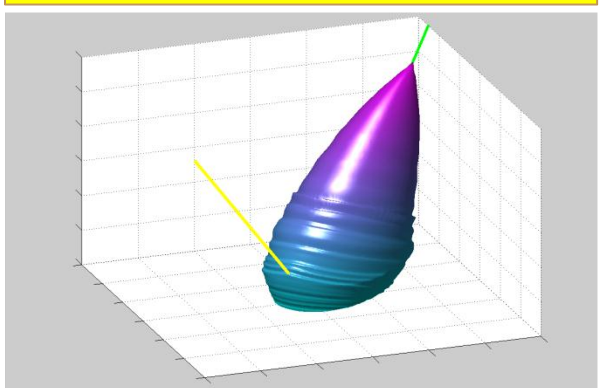
S/C Identification from Surface Characterization

Attitude Model



Wire-frame Shape Model

Candidate Material BRDFs

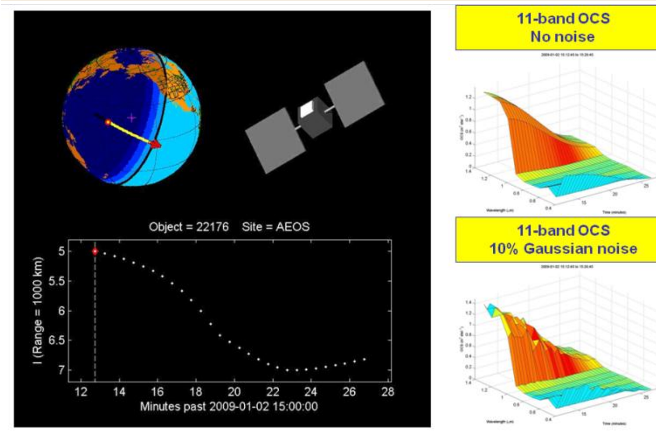


Assumed to be known

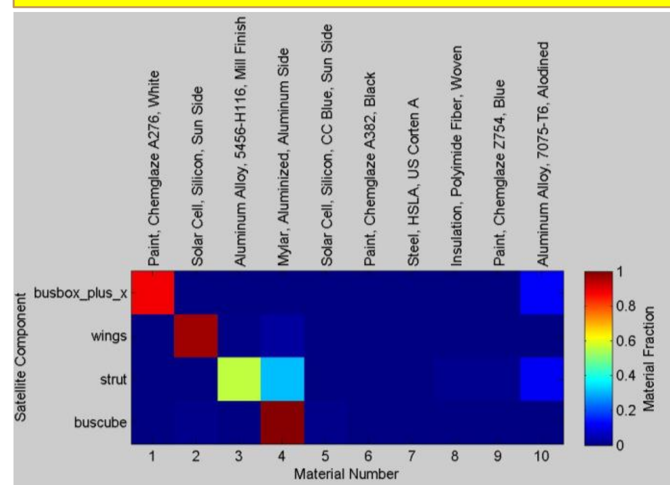
measurements

Analysis Process

Whole-body, Multi-band Observations



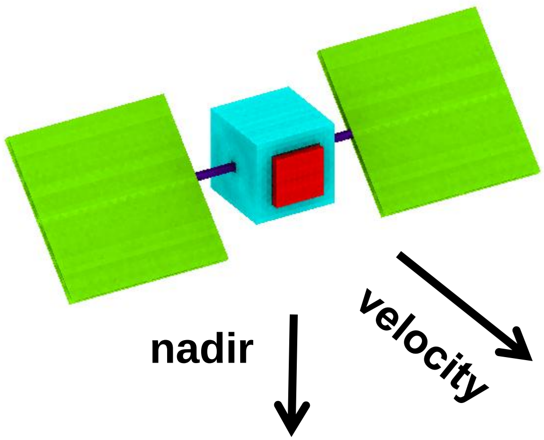
Best Material Identifications for Satellite Components



Paul Kervin, AFRL/RDS

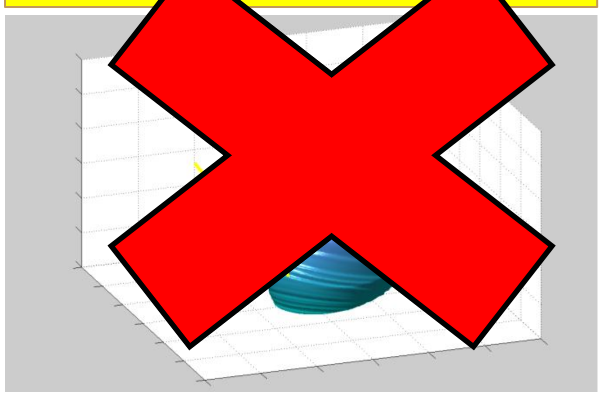
What is minimum data set for satellite identification?

Attitude Model



Wire-frame Shape Model

Candidate Material BRDFs

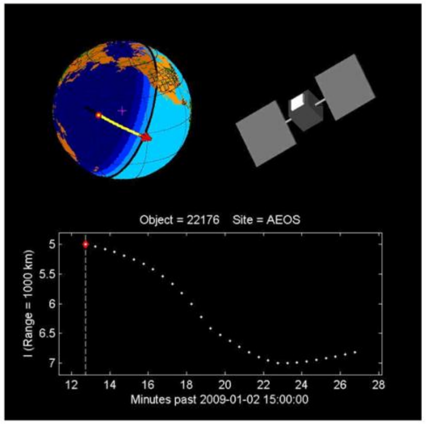


assumed a priori knowledge

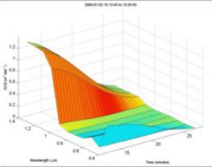
measurements

Analysis Process

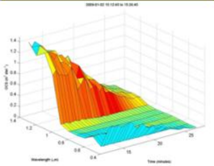
Whole-body, Multi-band Observations



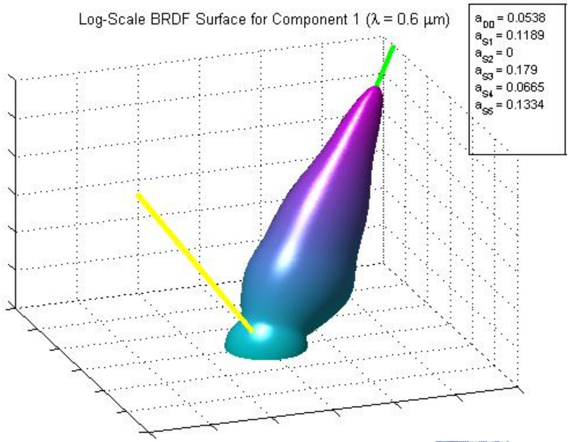
11-band OCS
No noise



11-band OCS
10% Gaussian noise

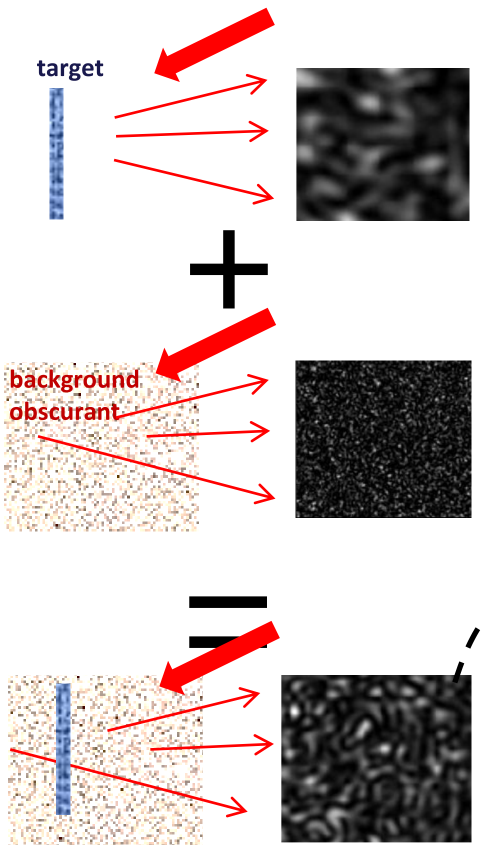


Retrieved BRDFs for all detected satellite components



No material BRDF library employed in retrieval

Coherent Sensing in the Presence of Diffusing Backgrounds or Obscurants



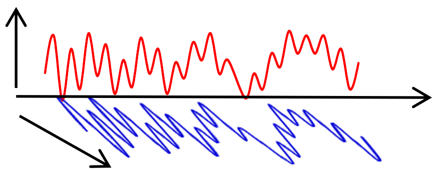
P - uniformly polarized but usually speckled (spatially partially coherent)

U - globally unpolarized and strongly speckled

Field available to sensor is the coherent superposition of both contributions

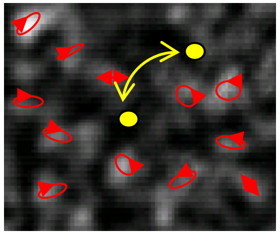
An analogous situation exists for spatially unresolved signals that vary in time. A similar sensing procedure can be developed where the spatial maps are replaced by time series of polarization resolved measurements

Step 1



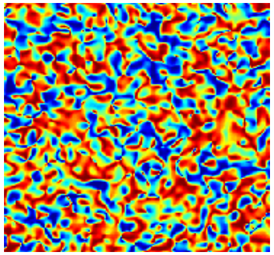
Extract the state of polarization by mixing the fluctuating field with an uncorrelated reference having the same mean optical frequency.

Step 2



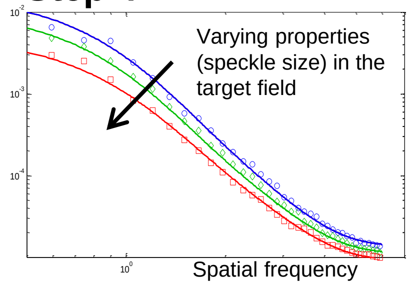
Determine the spatial distribution of polarization states of the measured field

Step 3



Map of similarity of polarization states wrt a reference (Complex Degree of Mutual Polarization)

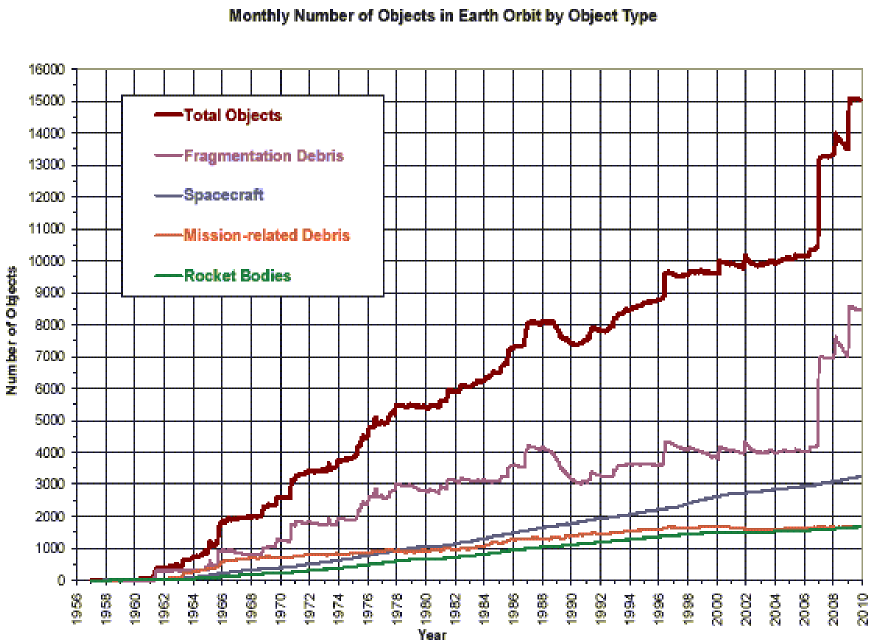
Step 4



- **Relative strength of field I_P can be found from the global degree of polarization; this is the target reflectivity**
- **Spatial properties of I_P relates to target morphology – size, shape, surface**

Opt. Express **19**, 15711 (2011)

Accurately Predicting the Location of Space Objects

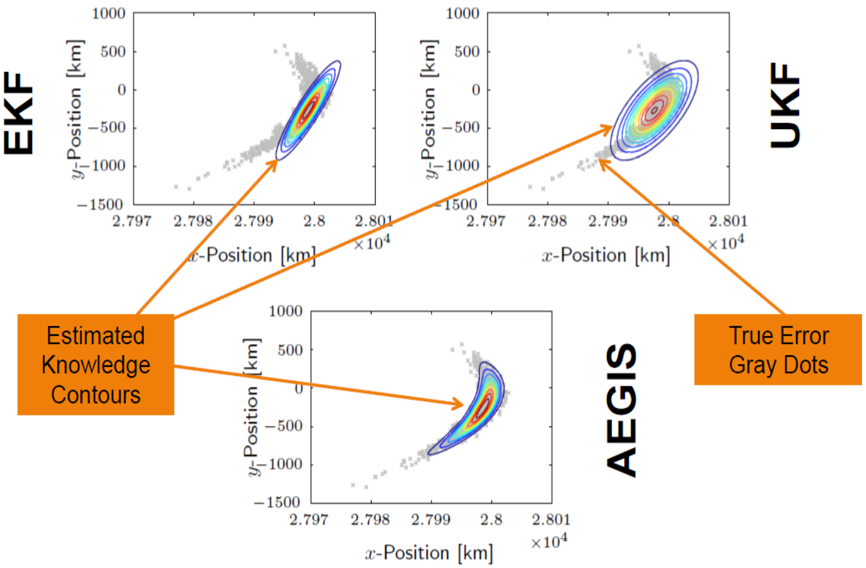


Cornerstone capability to all SSA

- **Challenges:**
  - Large number of objects (> 20,000 of size greater than 10cm)
  - Limited observations from multiple sensors
  - Non-Gaussian errors, uncertainty analysis
  - High fidelity models representing space weather
  - Conjunction analysis (combinatorial problem)
  - Closely spaced objects
  - Data association from diverse sensors
  - Optimal sensing for maximum information gathering and hazard assessment in a timely manner
  - Efficient computations

Accuracy of Orbit Predictions

- **Current uncertainty assumptions are Gaussian (e.g. constrained to error ellipses)**
  - AFSPC has shown that these uncertainties are often unrealistic
  - Uncertainty has wrong size and shape
- **Non-Gaussian uncertainties exist**
  - Objects that are tracked infrequently or detected for the first time
- **SSA requires realistic, quantifiable, and usable measures of orbit uncertainty (ambiguity)**
  - Correct knowledge leads to meaningful and appropriate UCT mitigation, collision probability computations, change detection, etc.

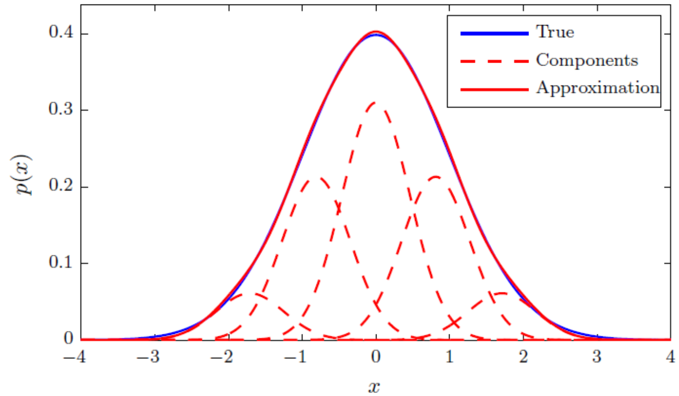


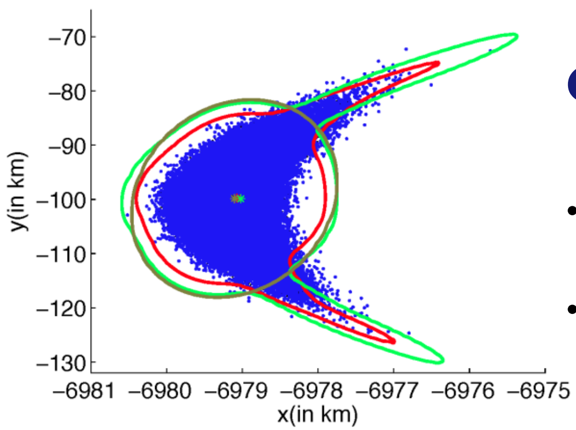
Accuracy of Orbit Predictions

Adaptive Entropy Gaussian Information Synthesis (AEGIS)

- Gaussian Sum approximations
- Information-Theoretic measures of ambiguity

Dr. Moriba Jah   AFRL/RV

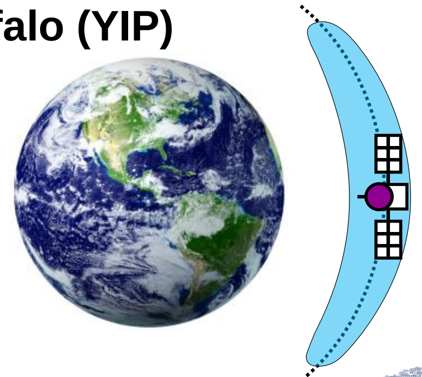




Generalized Polynomial Chaos (gPC) + Adaptive Gaussian Mixture Model (AGMM)

- Pose the optimal information collection problem as a stochastic control problem
- Performance and robustness metrics are derived in from information theory.

Dr. Puneet Singla, U Buffalo (YIP)

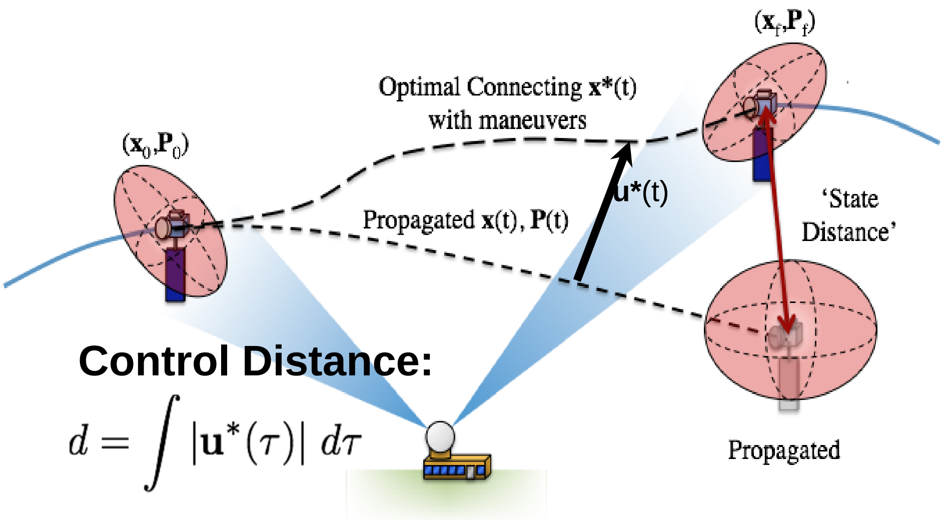


Multiple Hypothesis Tracking (MHT)

•Nonlinear filter
•Complexity of the Unscented Kalman Filter with the performance of a Gaussian Sum Filter

Dr Aubrey Poore, Numerica Corp.

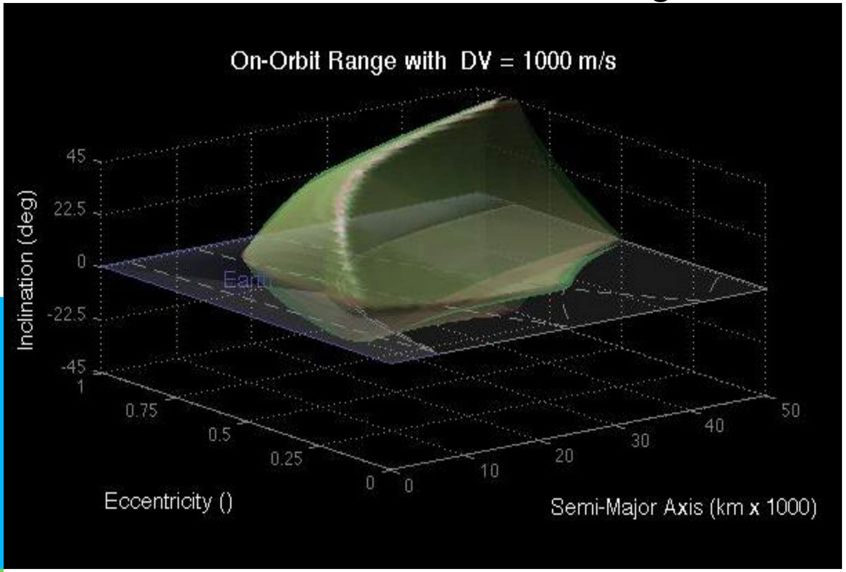
Rigorous Characterization of Thrusting Spacecraft



Control Distance:

$$d = \int |\mathbf{u}^*(\tau)|\, d\tau$$

Orbit Range in semi-major axis, eccentricity and inclination for a satellite starting in GTO



Surface encloses all possible orbit states reachable with a fuel budget of 1 km/s.

Objective

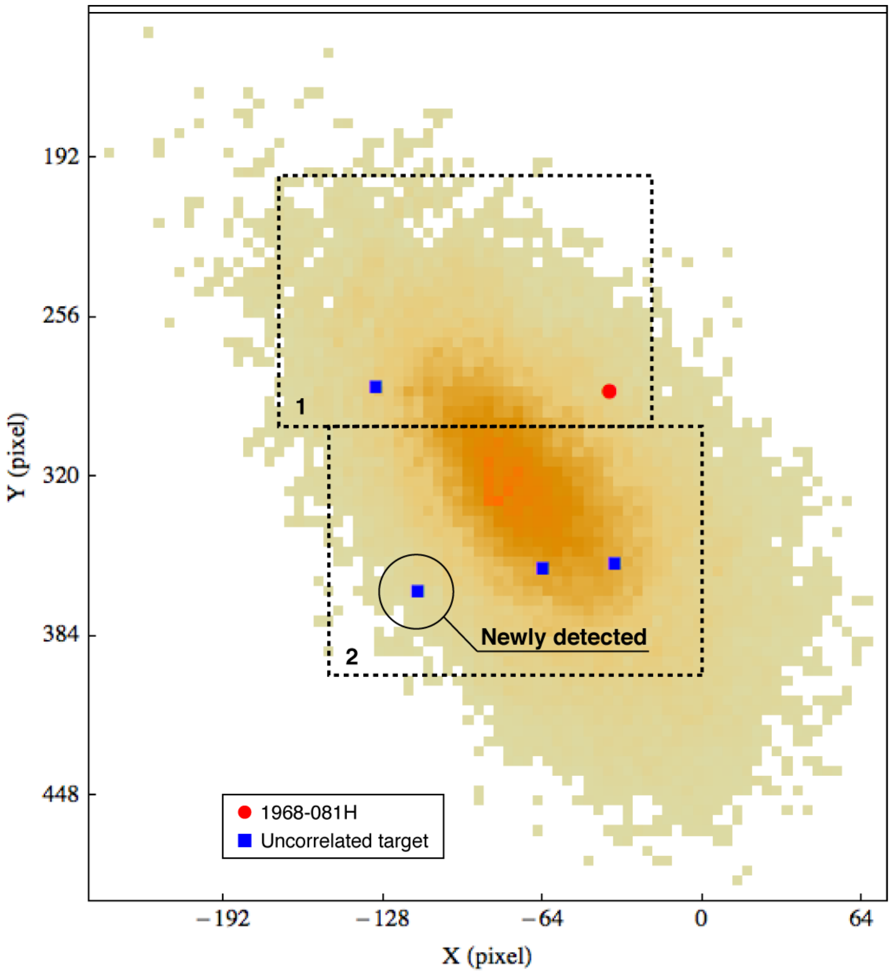
•A rigorous and hypothesis-free approach to characterizing the actions of a thrusting satellite
•Independent of whether it follows an impulsive, low-thrust, or natural force augmentation approach.

Approach

•Application of Optimal Control Theory
•Determine the limiting control expenditures to yield a change in state
•Discriminate between natural forces and artificial controls
•Delimit "orbit range" accessibility based on fuel costs.

D.J. Scheeres (University of Colorado)
K.T. Alfriend (Texas A&M University)

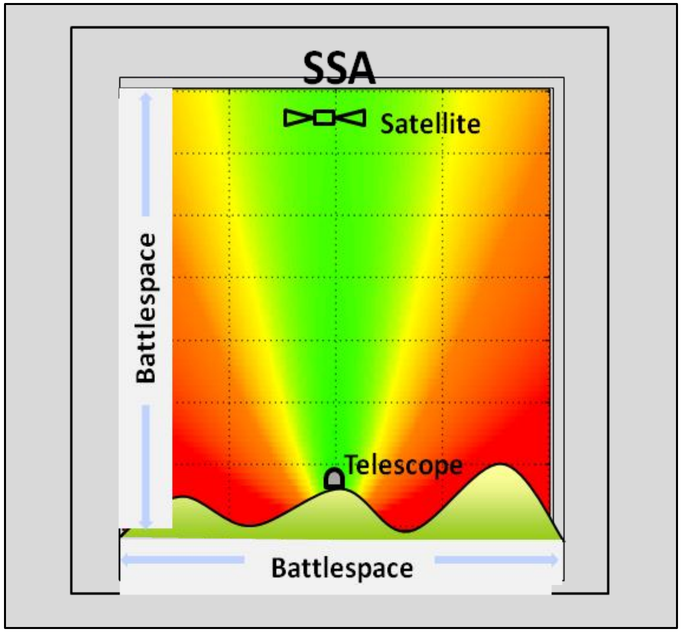
Low-luminosity Objects



- Object with luminosity lower than the limiting magnitude of a single image is successfully detected with a set of 32 successive images
- Combination of the Stacking Method with Motion Prediction reduces computation time by **a factor of 35**

Yukihito Kitazawa, IHI Corp
Toshiya Hanada, Kyushu U

Propagation through Deep Optical Turbulence



DE systems can't function across all parts of the battlespace.

Current efforts:

- MURI
- JTO MRI
- STTR
- YIP
- Conventional grants (4)
- Lab Tasks (2)
- AFIT (2)
- International research grant
- NATO Study

Horizontal Propagation Characterization and Compensation

Propagation Range

Green Beacon on AEOS

Laser beam from Haleakala

Experiment Description

- 3 laser beams at 0.532, 1.06 and 1.55 microns
- Mauna Loa on Hawaii (11,100 ft) to Haleakala on Maui (10,500 ft)
- Path range is 149 km

Observed Deviations

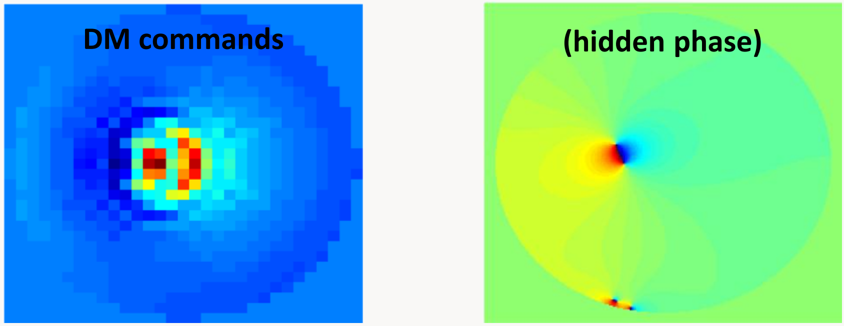
- Lack of stationarity and isotropy in the data
- Random motion of speckles and speckle pattern
  - -violates Frozen flow hypothesis
- Presence of unusually large amplitude spikes
  - -(coherent structures)
- 3 to 5 times larger measured intensity variance
- Aperture averaging is not effective for large apertures
- Failure to scale properly with wavelength changes

- **Approach 1: Wave propagation through conventional Anisotropic non-Kolmogorov turbulence**
  - Good match over 100 km paths at moderate turbulence between simulations and analysis
  - Phase screen simulations do not predict the COMBAT data behavior
  - Anisotropy of the atmosphere is of some influence but is not a major factor.

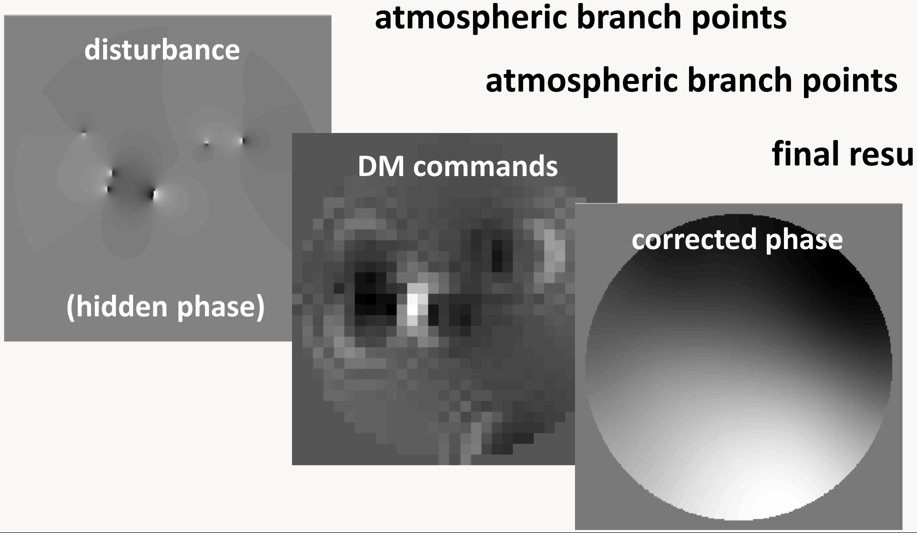
- **Approach 2: Use the Nosov turbulence spectrum with phase screen simulations**
  - Spectrum includes possible incipient turbulence and coherent structure formation in open air
  - Non-K exponents unrestricted, inner scales > 1 cm and outer scales < 1 meter
  - The substantial difference in the correlation functions at larger spacing not expected

Branch Points indicate the presence of Orbital Angular Momentum (OAM)

OAM pairs can be experimentally created on-demand



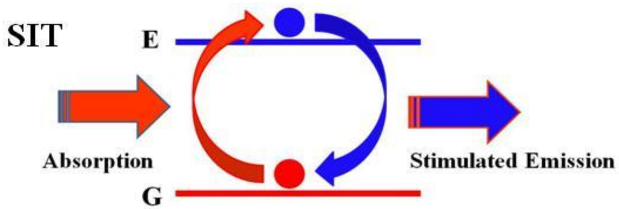
Deep Turbulence (branch points) can be expunged



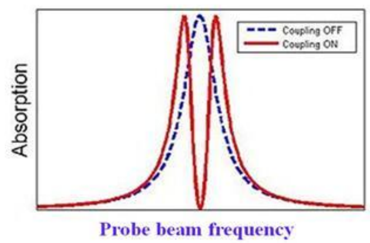
Headway into a problem previously thought to be intractable

Propagation of Polarization Modulated Beams through a Turbulent Atmosphere

SIT

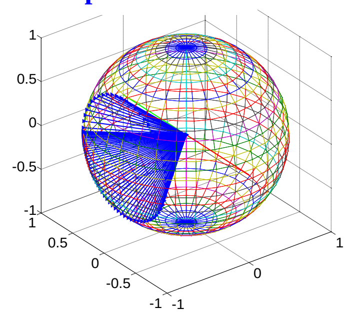


EIT



SIT & EIT well known, but pulse (transient) effects

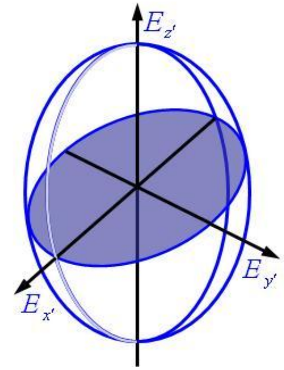
Poincare Sphere Representation



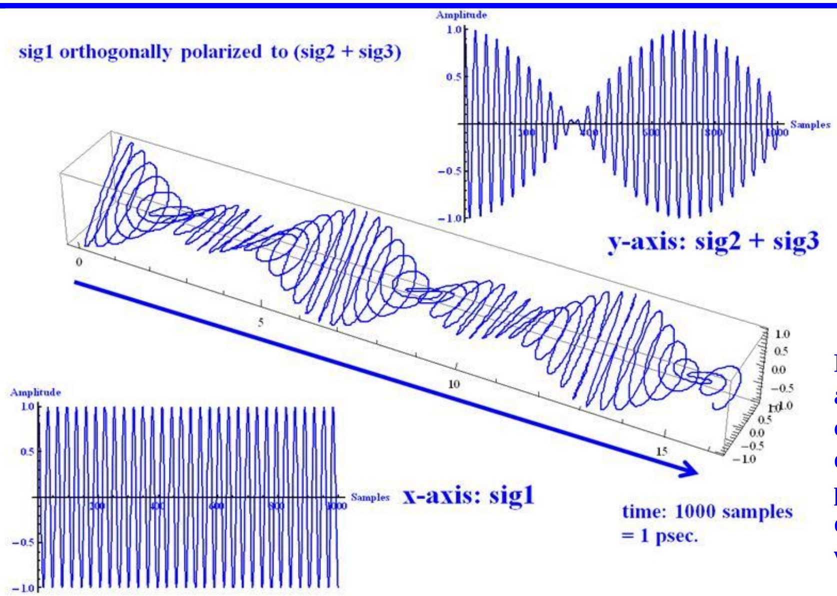
Polarization modulation (POLMOD) for CW beams: Transient in polarization compatibility, but , but using CW: POLMOD achieves CW-SIT & CW-EIT

SUSCEPTIBILITY TENSOR

$$\mathbf{P} = \varepsilon_0 \begin{bmatrix} \chi_{11} & \chi_{12} & \chi_{13} \\ \chi_{21} & \chi_{22} & \chi_{23} \\ \chi_{31} & \chi_{32} & \chi_{33} \end{bmatrix} \mathbf{E}$$



Tensor nature of susceptibility/refractive index/absorption/refraction: Describing anisotropic media



POLMOD achieved by combining two orthogonally polarized beams of different wavelength

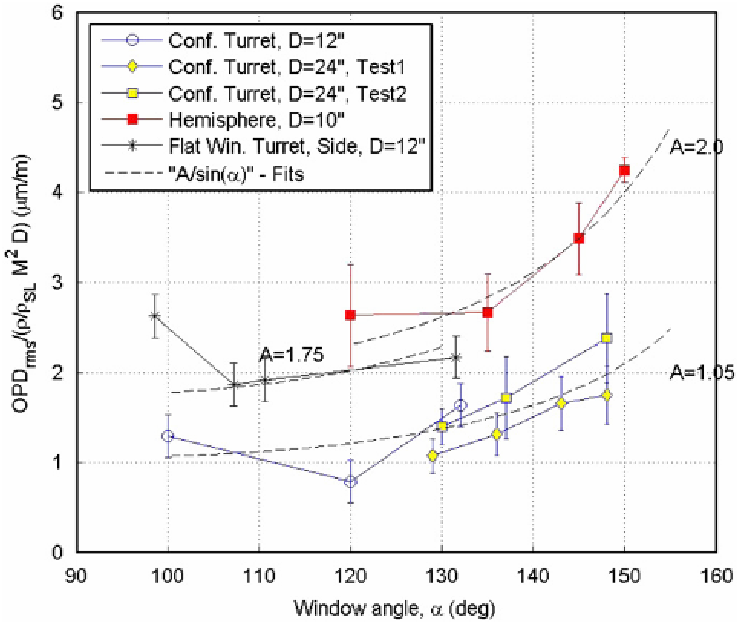
Transitions

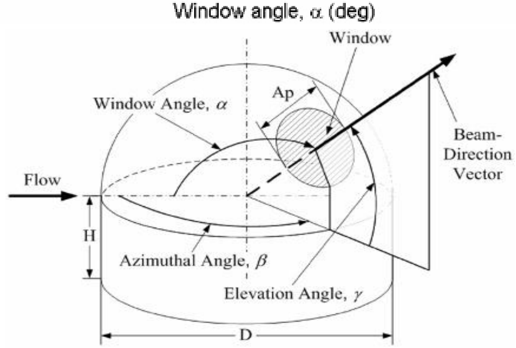
- **STTR** – Gravity model reformulation
  - Accurate high-speed gravity model for AFSPC
- **STTR** – Prediction of Satellite Ballistic Coefficients
  - Increased accuracy of drag prediction for AFSPC
- **STTR** – Synthetic scenery generation
  - Includes obscurants
- **STTR** – Beam control for optical phased arrays
  - Increased beam quality and higher power, extended beacons

- **JTO MRI** – Airborne Aero-Optics Laboratory

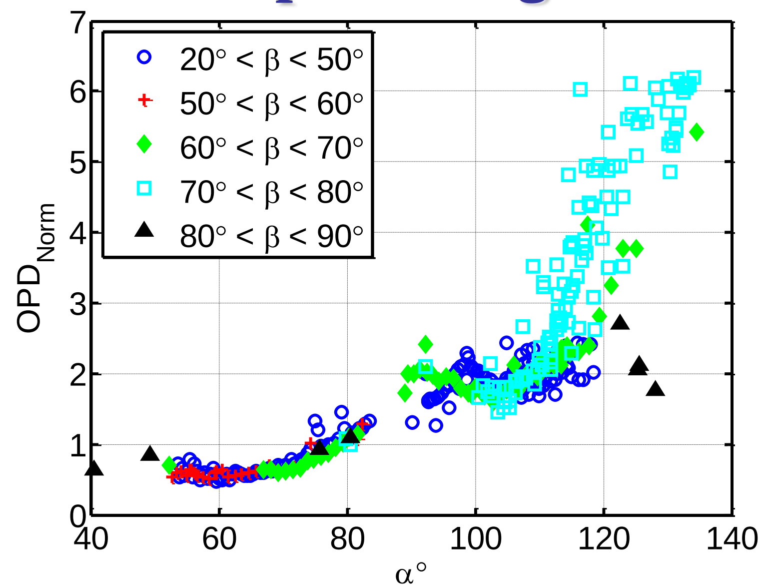
New Data from the AAOL

As of July 2010
All from Wind Tunnel

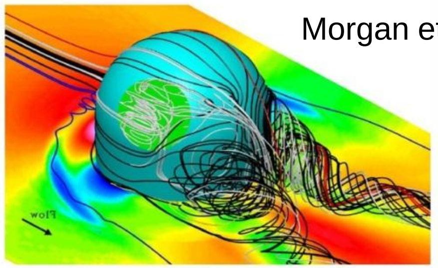




By February 2011
A Sample of Flight Data



Morgan et al., 2011



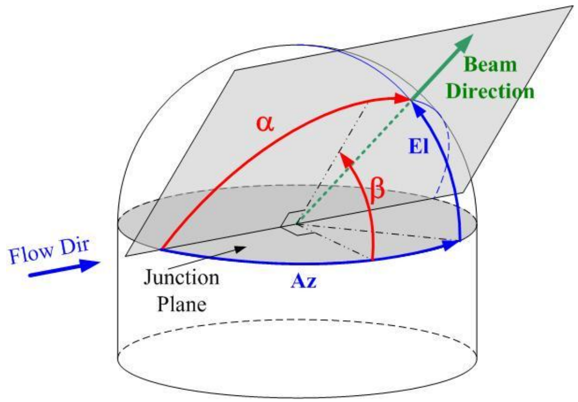
CFD confirmation and analysis

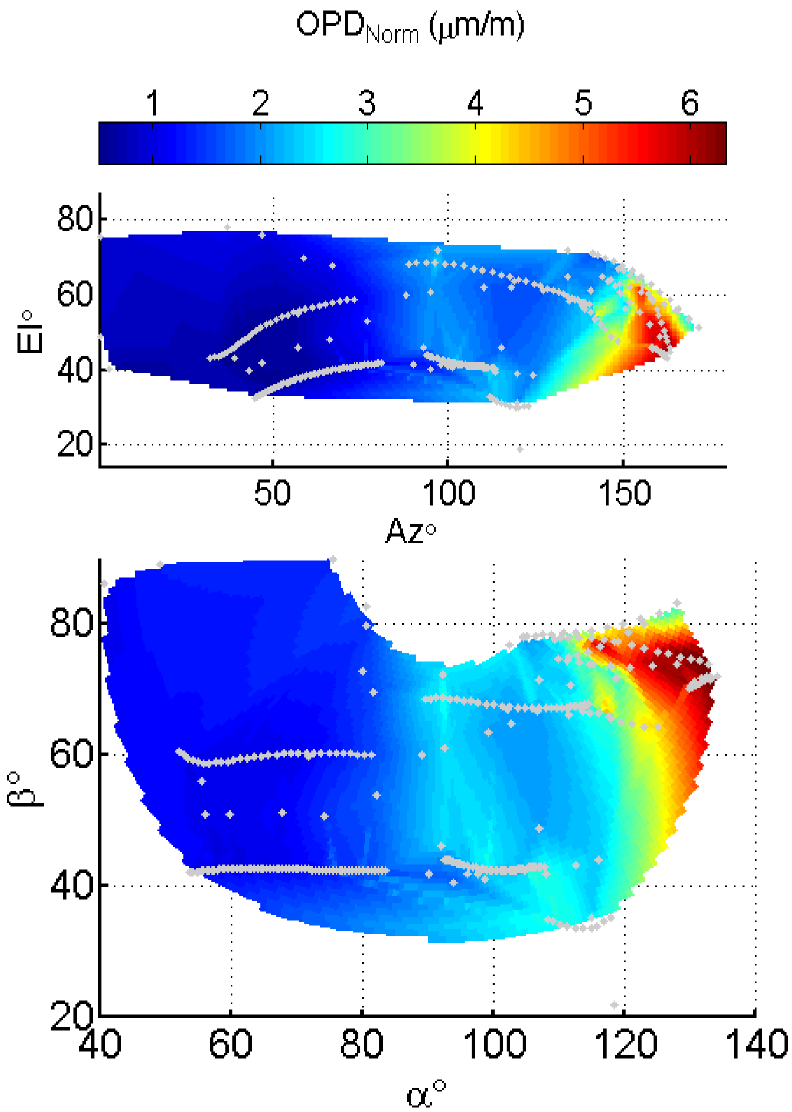
Optical Mapping around Turret

- **Normalized OPD**

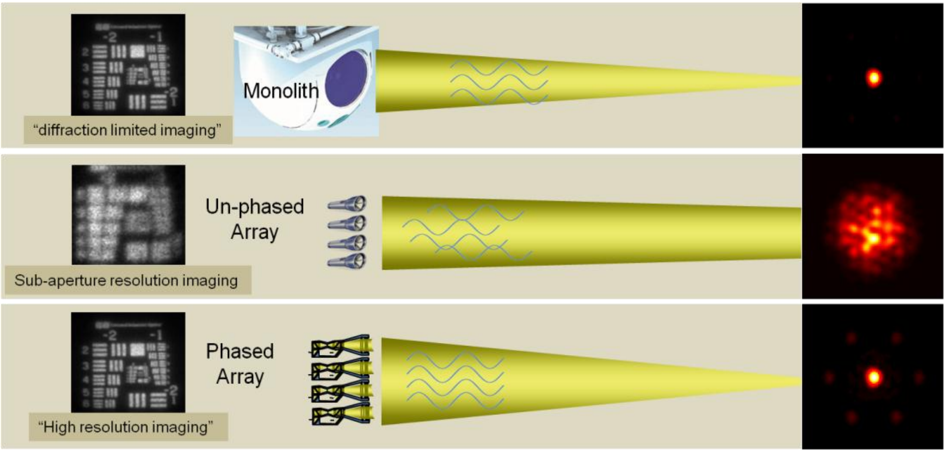
$$OPD_{Norm}\ (\mu m/m) = \frac{OPD_{RMS}}{((\rho_0/\rho_{SL})\ M^2\ D)}$$

- **Elevation angle does not affect forward looking angles**
- **Large increase in the normalized OPD_{RMS} at large backward off-center angles**
- **Centerline is a "relatively clean" region of the flow to look through at backward looking angles**





Beam Control for Optical Phased Arrays



Advantages of Phased Arrays:

- **Smaller & lighter**
  - An array of independent telescopes takes up less space and is lighter than a monolith and beam director
  - Master oscillator/power amplifier configuration with fiber amplifiers takes up less space and is lighter than a large laser
- **Conformal**
  - Telescope array is conformal to the surface
  - Conformal steering elements point the telescopes individually

Target Based Phased Array Technology

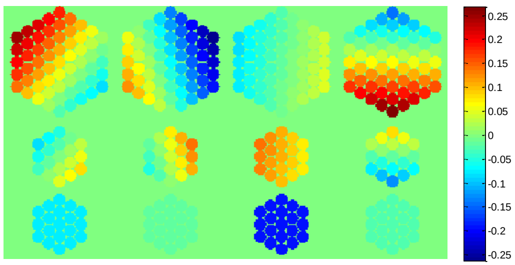
First Target Based Phasing Algorithm that Accommodates Speckle

The 4 Unobservable Modes Contain Array Tilt and Piston Associated with 3 Families of Aberrations

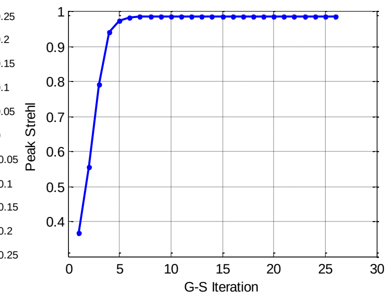
Speckle

Atmosphere

Telescope



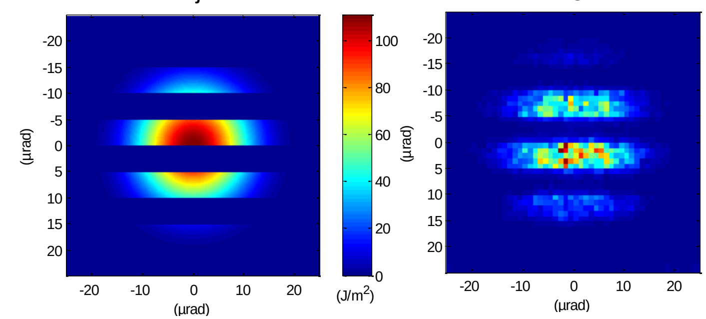
Exponential Class Piston Estimator Accommodates Unobservable Modes



Speckle Imaging Synthetic Aperture with Twice the Resolution of the Array for Aim Point Maintenance

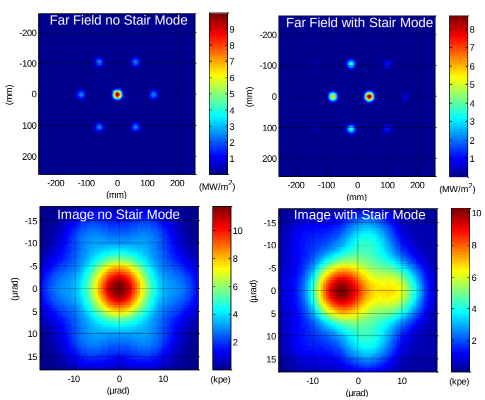
Object

Image

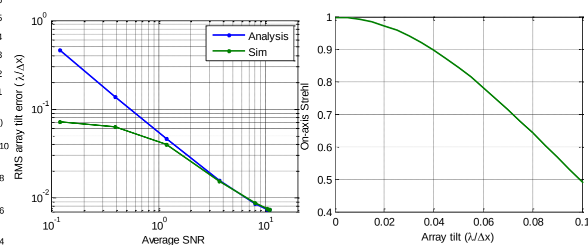


Stair Mode Imager with Matched Filter to Correct Array Tilt

Far Field Images with and without Stair Mode

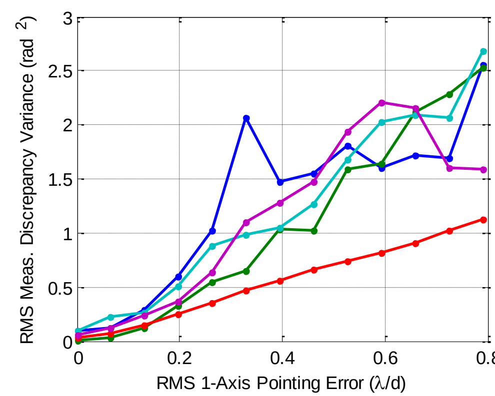


Matched Filter Accurately Predicts Array Tilt
(For SNR = 1, Strehl = 0.9)



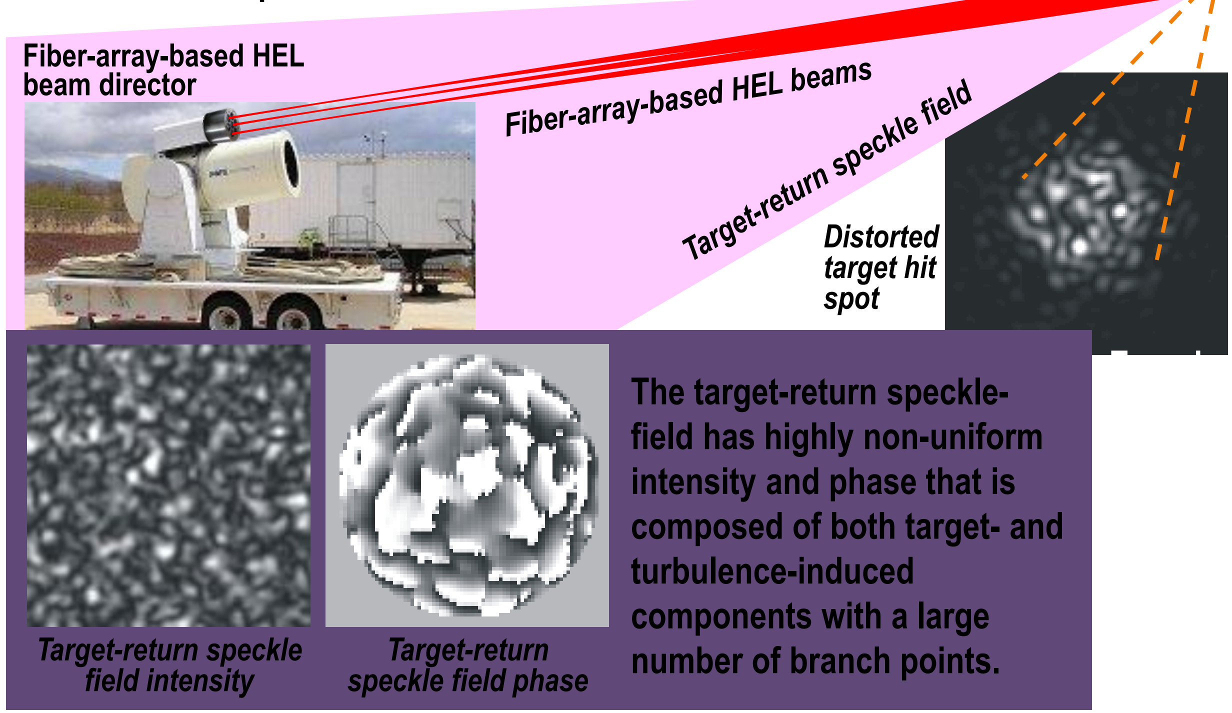
Measurement Discrepancy Scales with Boresight Error

(Addresses Multiple Bean Overlap at Target)



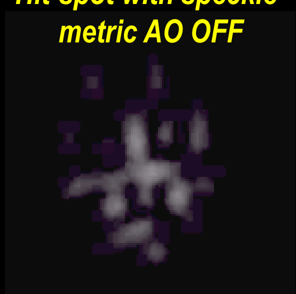
Speckle-Metric-Based Coherent Beam Combining

•Propagation of an HEL beam through turbulence leads to a highly distorted intensity footprint at the target surface (target hit spot).
•The hit-spot beam scattering off the extended target results in strong speckle modulation at the HEL beam director aperture.

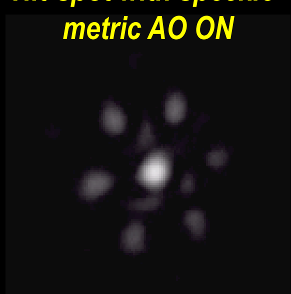


Experimental results

Hit-spot with speckle-metric AO OFF



Hit-spot with speckle-metric AO ON

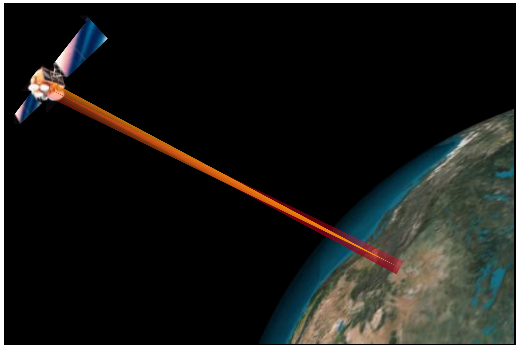


First experimental demonstration of fiber-array phasing on an extended moving target

Free-Space Quantum Key Distribution

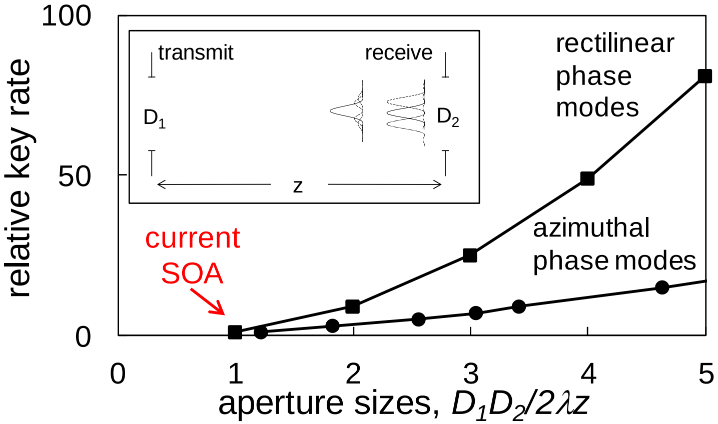
Quantum Key Distribution (QKD), based on single-photon quantum states

- Rapid on-demand generation of encryption keys among air, space, and ground communication nodes
- .Promises provable security with robustness to attacks from quantum computing
- Challenge is overcoming low key rates in free-space transmission

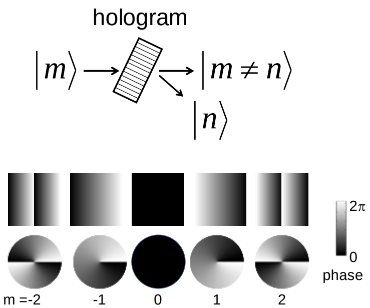


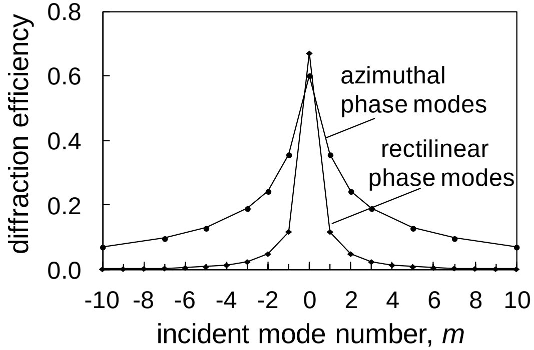
Approach:

- Utilize spatial modes of the optical field to achieve high keying rates.
- Challenge is to develop techniques for encoding and decoding photons with spatial modes of the optical field



Accomplishment: Validated mode decoding with transmission volume holograms





Mark Gruneisen, AFRL/RDS

Summary and Goals

- **Observing and Identifying Space Objects**
  - **Improved Imaging of Space Objects**
    - **Improvement of imaging capabilities at MSSS and SOR**
  - **Information without Imaging**
    - **Making Space Survillance effective without large telescopes**
  - **Predicting the Location of Space Objects**
    - **Determination and prediction of many orbits at high accuracy**

- **Remote Sensing in Extreme Conditions**
  - **Propagation Through Deep Optical Turbulence**
    - **Low elevation and long path AO, Active Imaging, and Laser Propagation**
  - **Beam Control**
    - **Good beam quality and imaging at higher power**